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RESEARCH PAPER

Fortification of yogurt with free and encapsulated persimmon (*Diospyros kaki* L.) extracts: Effects on antioxidant activity, phenolic contents, sensory and physicochemical characteristics

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Abstract

The encapsulation technique is a rapidly evolving technology with numerous beneficial applications in the dairy industry. Encapsulation methods are essential for enhancing the stability, functionality, and customization potential of dairy products. The aim of this study was to develop a new yogurt with enhanced sensory, nutritional, and antioxidant qualities by incorporating alginate-encapsulated persimmon (*Diospyros kaki* L.) extracts. The titratable acidity, pH, whey syneresis, water holding capacity, color parameters (L^*, a^*, b^*, ΔE^*_{ab}), sensory characteristics, phenolic content, and antioxidant activity of yogurt samples [C (control), FP-1 and FP-5 (containing 1% and 5% free persimmon extract, respectively), and MP-1 and MP-5 (containing 1% and 5% alginate-encapsulated persimmon extract, respectively)] were evaluated on the 1st and 21st days of storage. In the main findings, the variations between samples in terms of L^* and ΔE^*_{ab} values on the first day of storage were found to be significant ($p < 0.05$). The highest ΔE^*_{ab} values were found on the first day of storage for MP-5 and MP-1, with 9.46 ± 0.41 and 7.94 ± 1.48, respectively ($p < 0.05$). Samples with encapsulated extracts demonstrated greater antioxidant potential and phenolic content compared to those with free extracts, due to the enhanced preservation of phenolic compounds and their improved bioavailability ($p < 0.05$). The overall acceptability scores of the yogurt samples during the storage period indicated that the highest score was achieved by treatment (MP-5), which involved yogurt with 5% alginate-encapsulated persimmon ($p < 0.05$).

Encapsulation of persimmon extract by extrusion effectively enhanced its stability and enabled its use as a functional ingredient in yogurt. The fortified yogurts remained stable throughout storage and offered improved bioactive properties and favorable sensory characteristics, suggesting potential as a novel functional dairy product.

Keywords

Bioactive compounds, Encapsulation, Fruit extracts, Functional Dairy Products

Introduction

Fermentation is widely applied across the globe to improve the shelf life, sensory attributes, and nutritional composition of raw materials. Fermented products are often considered functional foods due to their content of bioactive compounds and their beneficial interactions with the human microbiome (Valentino et al. 2024). Recent studies emphasize the growing interest of the food industry in fermented and functionalised foods, particularly those developed through targeted fermentation processes. Such approaches, especially when employing selected starter cultures, have been shown to enhance the bioavailability and functionality of food components, supporting their use in both nutrition and health-oriented applications (Abdul Hakim et al. 2023;

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Dong et al. 2024). In line with these developments, recent trends in functional food production have focused on creating nutrient-dense products enriched with bioactive compounds. Among these, fermented dairy products—particularly yogurt and fortified yogurt—account for more than 70% of the global functional food market, highlighting their central role in the advancement of functional food technologies (Taksima et al. 2015; Vulić et al. 2019; Hadjimbei et al. 2022). The health benefits of yogurt have contributed to its widespread popularity worldwide. Additionally, this fermented dairy product plays several roles in human health by providing a substantial amount of natural nutrients and enhancing microflora with probiotic strains and other lactic acid bacteria. Research in the field of fermented dairy products has increasingly shifted towards incorporating ingredients with various synbiotic or bioactive properties. This approach aims to develop yogurts with enhanced nutritional, sensory, physicochemical, and rheological characteristics compared to traditional products (Fazilah et al. 2018). Persimmon (*Diospyros kaki* L.) is a fruit valued in numerous countries for its sensory properties, high nutritional quality—thanks to its fibers, vitamins, and phenolic compounds—and its versatility for use in various industrial sectors (Milczarek et al. 2018; Ferrara 2021). Persimmon is rich in various macro and micronutrients, demonstrating significant bioactivity. Notably, the fruit contains key nutrients such as carbohydrates, organic acids, phenolic compounds, carotenoids, and tannins (Hernández-Carrión et al. 2014; Yaqub et al. 2016; Persic et al. 2018; Matheus et al. 2022), which contribute to its antioxidant, cytotoxic, and antidiabetic properties (Giordani et al. 2011; Sharma et al. 2024). Persimmon fruit offers various health benefits, including protection against diabetes, high blood pressure, cough, diuretic effects, and numerous viral and bacterial infections, such as dental caries (Yaqub et al. 2016). These beneficial effects are attributed to the presence of several bioactive compounds, including carotenoids and polyphenols, which are crucial in preventing degenerative diseases (Choudhary et al. 2023). Additionally, persimmon fruit is widely used in developing a range of products due to its functional properties (Kaur et al. 2022). Fruit-based yogurt is a popular and refined type of yogurt that is enjoyed by people worldwide. The combination of various fruits enhances the visual appeal of fruit yogurt (Mojikon et al. 2022). Adding fruit to yogurt improves its formulation, enhances flavor, and results in a tasty product with refreshing and health-promoting benefits (Rashwan et al. 2023). Encapsulation serves several key roles in food applications, such as protecting the core material's reactivity from environmental factors like light, water, and oxygen, and regulating the rate at which this active material is released into the surrounding environment. Additionally, it aids in the uniform dispersion of bioactive compounds and simplifies handling by preventing clumping. For this reason, it is essential that the outer coating has a high affinity for the other ingredients in the mixture to facilitate the solubilization and even distribution of the encapsulated material (Mehta et al. 2022). Furthermore, the coating manages the release of the encapsulated content, masks any undesirable properties like off-flavors, and helps dilute the encapsulated material when the bioactive compounds are required in small amounts (Sbehat et al. 2022). Alginate-based encapsulation offers remarkable protection for encapsulated substances and allows for controlled release under specific conditions, such as pH changes or the introduction of chelating agents. Alginate gel beads can effectively encapsulate components like probiotics, enzymes, and flavors, ensuring their protection and regulated release in dairy products. This method is especially advantageous for encapsulating probiotics in yogurts and other fermented dairy items (Adinepour et al. 2022; Nezamdoost-Sani et al. 2023; Paul et al. 2025). In the last twenty years, there has been significant interest in developing a new range of dairy products that, while similar to existing ones, are enhanced with functional compounds (Vulić et al. 2019; Adinepour et al. 2022). The task of creating new foods enriched with biologically active ingredients is a contemporary challenge in nutritional science and practice. Many of these compounds are unstable when added to food matrices, necessitating methods to stabilize them prior to incorporation. Encapsulation is a technique that helps maintain the stability of these substances in food products. To successfully integrate encapsulated biologically active ingredients into milk and dairy products, it is essential to have a thorough understanding of their chemical properties and technological characteristics (El-Sayed et al. 2024; Bhtoya et al. 2025).

To the best of our knowledge, there are no reports on the incorporation of persimmon extract encapsulated in alginate beads into yogurt. The aim of this study was to develop a new yogurt with enhanced sensory, nutritional, and antioxidant qualities by incorporating alginate-encapsulated persimmon (*Diospyros kaki* L.) extracts.

Materials and methods

Materials

Persimmon fruits were purchased from local market (Zonguldak, Turkey). The persimmon fruits used in this study belonged to the 'Fuyu' cultivar, one of the most widely cultivated and consumed varieties worldwide due to its firm texture and sweet flavor. The persimmon fruits selected for this study had a °Brix value of approximately 15, measured using a KRÜSS digital refractometer (Model DE75167706), indicating optimal ripeness suitable for extract preparation. Yogurt was prepared using sterilized whole cow's milk, which was sourced from a local market in Zonguldak. To increase the solids content, skimmed milk powder (NFMP) was added, obtained from Pınar Süt Ürünleri in İzmir. A frozen starter culture (YC-350), consisting of *Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *bulgaricus*, was provided by Chr. Hansen Co. (A/S, Horsholm, Denmark). ABTS (2,2-azinobis (3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt), Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid), and gallic acid were supplied by Acros (Morris Plains, NJ, USA).

For this study, the Folin-Ciocalteu reagent was procured from Merck, which is located in Darmstadt, Germany. Potassium persulfate ($K_2S_2O_8$), sodium carbonate (Na_2CO_3), sodium alginate, sodium chloride (NaCl) and calcium chloride ($CaCl_2$) were purchased from Sigma-Aldrich, which is situated in St. Louis, MO. All the reagents and chemicals used in this study were of analytical grade.

Preparation of persimmon fruits

The persimmon fruits were washed, their peels and seeds were removed, and the flesh was cut into small pieces. Following addition of distilled water in 1:2 ratio, samples were homogenized with a laboratory homogenizer (Homogenizer T 65, Ika, Staufen, Germany), filtered through straining cloths and pasteurized in a water bath at 85 °C for 20 minutes. The obtained persimmon filtrates were used for the preparation of free extract and encapsulated in alginate beads.

Preparation of alginate beads

Sodium alginate (2 g) and 1 g NaCl was suspended in 100 ml persimmon extract followed by heating at 50 °C for 3 min and stirring with a laboratory homogenizer (Homogenizer T 65, Ika, Staufen, Germany) for 2 min. The procedure was as described in the details (Vlaseva et al. 2014) and finally, alginate suspension was dropped into a cold 2% calcium chloride solution. The resulting alginate beads were washed with distilled water and were used for incorporation into yogurt (Fig. 1).

Figure 1. Alginate beads with persimmon extracts.

Production of yogurt

Cow milk with 3% fat, 3.6% protein, 12.1% total solids, and 8 SH acidity was used for yogurt preparation (Tamime and Robinson 1999). Skimmed milk powder was added to raise the total solid content to 15% (15 grams per 100 grams), and the mixture was homogenized using a Homogenizer T 65 (Ika, Staufen, Germany). The milk was then pasteurized at 85 °C for 30 minutes. After the milk cooled to approximately 42–45 °C, the free persimmon extract (1%, 5%) and persimmon microspheres (1%, 5%) were added to the milk and mixed for some time.

Following this, *Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *bulgaricus* were introduced to the mixture at a concentration of 2% (w/v). The milk was then incubated at 42 ± 1 °C until the pH reached 4.6–4.7, which took around 3.5 hours. After incubation, the yogurt samples were stored at 4 ± 1 °C for a period of 21 days. The procedure was repeated twice, and the samples were analyzed on the 1st and 21st days of storage. The yogurt samples were separated into five batches: C (control), FP-1 and FP-5 (containing 1% and 5% free persimmon extract, respectively), and MP-1 and MP-5 (containing 1% and 5% alginate-encapsulated persimmon extract, respectively) (Fig. 2).

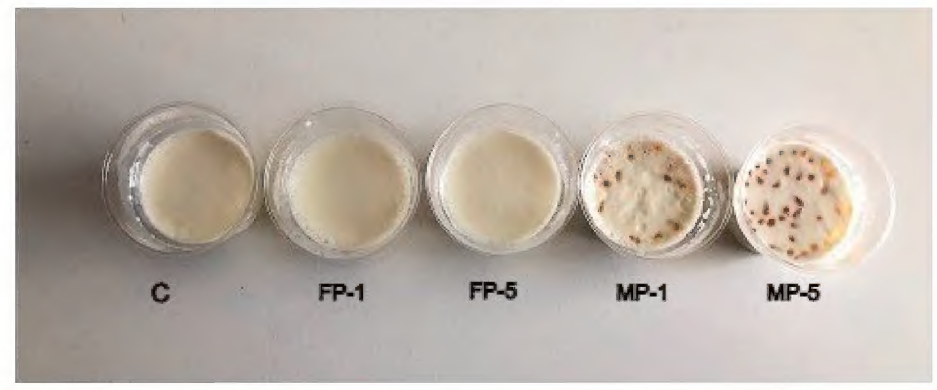

Figure 2. Yogurt samples. C (control), FP-1 and FP-5 (containing 1% and 5% free persimmon extract, respectively), and MP-1 and MP-5 (containing 1% and 5% alginate-encapsulated persimmon extract, respectively).

Characterization of yogurt

Physicochemical methods

Titratable acidity was assessed as the equivalent of lactic acid following the method described by Case et al. (1985). The pH of the samples was measured using a digital pH meter (Schott Instruments, Lab 860, Germany). Whey syneresis was evaluated by placing 25 grams of yogurt on filter paper within a funnel and measuring the amount of whey separated after 2 hours at 4 °C (Tamime et al. 1996). Each yogurt sample (10 g) was centrifuged at 4100×*g* at 4 °C for 30 minutes for the water holding capacity (WHC) test (Nourmohammadi et al. 2020). The whey was weighed, and the WHC was calculated using the following Equation (1):

$$\text{WHC (\%)} = [1 - (\text{Whey weight/initial weight})] \times 100$$

Colour properties

The reflected color of the yogurt samples was measured at 1 and 21 days of storage to determine any changes in color.

Color analysis was carried out in the present study using a CHN Spec. Spectral Colorimeter (Model CS-410, China) and the CIELab color scale with illuminant D65 and 10° viewing angle. The color parameters examined included luminosity (L*), red and green intensity (a*), and yellow and blue intensity (b*) (Zhao et al. 2023). Total color change (ΔE^*_{ab}) was calculated using equations (2) to assess the overall difference in color between the control and other samples, according to Chao et al. (2023). For each yogurt sample, three measurements were obtained at each sampling time.

The value of the ΔE was obtained using Equation (2):

$$\Delta E^*_{ab} = [(L^*_0 - L^*)^2 + (a^*_0 - a^*)^2 + (b^*_0 - b^*)^2]^{1/2}$$

Total antioxidant activity

The ABTS-TEAC assay involved using 2,2'-azino-bis(3-ethylbenzothiazoline)-6- sulfonic acid

To prepare the ABTS+ radical cation, 7 mM ABTS stock solution was reacted with 2.45 mM potassium persulfate. The resulting ABTS+ solution was then diluted using PBS (pH 7.4) until it reached an absorbance of 0.70 (± 0.02) at 734 nm, stabilized at 30 °C. The inhibition of ABTS+ by Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid) was measured spectrophotometrically at 734 nm using a Shimadzu instrument (Shimadzu Scientific Instruments, Inc., Tokyo, Japan). The TEAC values were calculated based on the Trolox standard curve and expressed as Trolox equivalents (μmol / mL) in the sample (Re et al. 1999).

Total phenolic content analysis

The phenolic content of the yogurt was analyzed using gallic acid as a reference standard, following the Folin-Ciocalteu method (Singleton and Rossi 1965). Absorbance was measured at 760 nm using a spectrophotometer (Shimadzu Scientific Instruments, Inc., Tokyo, Japan). The results were expressed in terms of milligrams of gallic acid equivalents (GAE) per kilogram of sample.

Sensory analysis

The sensory evaluation of the samples was conducted by a panel of 10 trained evaluators (5 males and 5 females) using sensory evaluation scorecards. The panelists were aged between 25 and 34 years. The samples were assessed across five distinct categories. On the 1st and 21st storage days, the yogurts were rated on a 10-point scale for appearance, consistency, taste and aroma, odor, and overall acceptability, following the methodology outlined by Lawless and Heymann (1999).

Statistical analysis

The entire experimental procedure and subsequent analyses were conducted twice. The data were processed using SPSS for Windows version 16.0. A repeated measures one-way analysis of variance (ANOVA) was employed for the statistical analysis, with a significance level set at $p < 0.05$. Duncan's multiple range test was used to assess the differences between the repeated data (SPSS 2017).

Results and discussion

Physicochemical parameters

Table 1 illustrates the alterations in the chemical properties of yogurt samples over the course of storage. Changes in pH, whey syneresis, water holding capacity, and titratable acidity values over time were found to be significant ($p < 0.05$). An increase in titratable acidity and a decrease in pH levels were noted throughout the storage period, along with a reduction in water holding capacity and whey syneresis an increase in values. The reduction in pH was likely caused by the increased bacterial metabolic activity, which resulted in the production of higher amounts of lactic acid through the hydrolysis of lactose (Dai et al. 2016).

Table 1. The physicochemical composition of yogurt samples.

Sample	Storage periods (day)	Titratable acidity (LA%)	pH	Whey syneresis (%)	Water holding capacity (%)
C	1	1.17 ± 0.01 ^{Aa}	4.61 ± 0.02 ^{Bb}	7.90 ± 0.06 ^{Ba}	65.66 ± 0.12 ^{Bb}
	21	1.27 ± 0.01 ^{Bb}	4.25 ± 0.00 ^{Ba}	12.38 ± 0.22 ^{Bb}	62.80 ± 0.22 ^{Ba}
FP-1	1	1.33 ± 0.01 ^{Ba}	4.48 ± 0.01 ^{Ab}	7.40 ± 0.12 ^{Ba}	63.88 ± 0.63 ^{Ab}
	21	1.40 ± 0.02 ^{Aa}	4.19 ± 0.01 ^{Aa}	12.25 ± 0.14 ^{Bb}	61.13 ± 0.20 ^{Ba}
FP-5	1	1.20 ± 0.01 ^{Aa}	4.54 ± 0.01 ^{Ab}	7.95 ± 0.03 ^{Ba}	62.44 ± 0.13 ^{Ab}
	21	1.25 ± 0.02 ^{Ba}	4.16 ± 0.00 ^{Aa}	14.13 ± 0.07 ^{Ab}	56.54 ± 0.45 ^{Aa}
MP-1	1	1.25 ± 0.01 ^{Ba}	4.47 ± 0.01 ^{Ab}	7.25 ± 0.14 ^{Ab}	71.50 ± 0.17 ^{Aa}
	21	1.35 ± 0.02 ^{Ab}	4.19 ± 0.00 ^{Aa}	4.78 ± 0.01 ^{Aa}	82.07 ± 0.10 ^{Ab}
MP-5	1	1.14 ± 0.01 ^{Aa}	4.53 ± 0.00 ^{Ab}	6.13 ± 0.07 ^{Ab}	78.45 ± 0.10 ^{Aa}
	21	1.14 ± 0.01 ^{Aa}	4.30 ± 0.01 ^{Ba}	4.75 ± 0.14 ^{Aa}	89.54 ± 0.54 ^{Ab}

C: Yogurt control sample; FP-1: Yogurt with 1% free persimmon extract; FP-5: Yogurt with 5% free persimmon extract; MP-1: Yogurt with 1% alginate-encapsulated persimmon; MP-5: Yogurt with 5% alginate-encapsulated persimmon.

$^{a–b}$ Different lowercase superscripts in the same row indicate significant differences among storage times ($p < 0.05$).

^{AB} Different uppercase superscripts in the same column indicate significant differences among yogurt samples at the same storage time ($p < 0.05$).

When the results of serum separation and water-holding capacity were examined, it was observed that the changes in MP-1 and MP-5, in particular, were significant compared to the control sample ($p < 0.05$). While the serum separation values of MP-1 and MP-5 samples decreased during the storage process, their water-holding capacities increased ($p < 0.05$). In this context, it was concluded that the encapsulated samples are also highly acceptable in terms of physical criteria. These findings are consistent with those previously reported by Yadav et al. (2018), El-Kholy et al. (2019), Tumbarski et al. (2024).

Colour properties

One of the key factors influencing consumers' perception of quality is the color of the product. The appearance of color is one of the most appealing characteristics of food, providing a foundation for assessing its freshness and quality (Šeregelj et al. 2019). The physical color parameters of the yogurt samples are shown in Table 2. The variations between samples in terms of L^* and ΔE^*_{ab} values on the first day of storage were found to be significant ($p < 0.05$). If the ΔE^*_{ab} value is greater than 5, consumers can detect changes in product color (Castellar et al. 2006; Britto et al. 2020). The highest ΔE^*_{ab} values were found on the first day of storage for MP-5 and MP-1, with 9.46 ± 0.41 and 7.94 ± 1.48, respectively ($p < 0.05$). The addition of encapsulated persimmon to the yogurt samples resulted in a positive change in ΔE^*_{ab} values in terms of consumer acceptance compared to the control samples. Comparable findings were documented by Yadav et al. (2018), El-Kholy et al. (2019) and Taşdemir and Gölge (2024) in their studies on encapsulation of different components in yogurt.

Assessment of the overall antioxidant activity and phenolic content

Fig. 3 presents the total antioxidant activity of yogurt samples throughout the storage period. According to the antioxidant activity results, the variation between the samples and the time-dependent changes within the same sample were found to be significant ($p < 0.05$). Samples with encapsulated extracts demonstrated greater antioxidant potential compared to those with free extracts, due to the enhanced preservation of phenolic compounds and their improved bioavailability ($p < 0.05$). These results are consistent with those previously reported by El-Kholy et al. (2019), Šeregelj et al. (2019), Šeregelj et al. (2021), and Tumbarski et al. (2024). A direct correlation exists between polyphenol concentration and antioxidant activity (Delfanian and Sahari 2020), as higher concentrations result in an increased number of hydroxyl groups in phenolic compounds. This, in turn, raises the likelihood of hydrogen donation to free radicals, thereby enhancing the extract's inhibitory capacity (Zhang et al. 2010; Li et al. 2021). As a result, encapsulating persimmon in microspheres demonstrated a strong antioxidant capacity and enhanced its antioxidant potential for use in the development of functional foods. Moreover, the degradation of protein aggregates and protein–polyphenol bonds over the storage period may enhance the extractability of polyphenols and increase their overall content. This pattern was also noted by Yadav et al. (2018), who examined the antioxidant capacity, composition, and sensory properties of yogurts enriched with encapsulated grape seed extract. In the referenced study, it was reported that the yogurt sample with encapsulated grape seed extract showed a threefold increase in total phenolic content and a fourfold enhancement in antioxidant activity compared to the control group (Yadav et al. 2018).

Phenolic compounds, a significant class of plant secondary metabolites, are synthesized in response to environmental stressors. Their hydroxyl groups enable them to neutralize free radicals and function as electron or hydrogen donors (Lončarević et al. 2019). Additionally, these compounds demonstrate antioxidant properties by preventing the breakdown of hydroperoxides into free radicals (Godocikova et al. 2017). Fig. 4 shows the total phenolic content of yogurt samples over the storage period. Based on the total phenolic content, the

Table 2. The physical color parameters of yogurt samples.

Sample	Storage periods (day)	L^*	a^*	b^*	ΔE^*_{ab}
C	1	70.14 ± 1.50 ^{Aa}	-0.47 ± 0.02 ^{Aa}	7.97 ± 0.11 ^{Aa}	-
	21	73.63 ± 1.13 ^{Aa}	-0.37 ± 0.08 ^{Aa}	8.10 ± 0.16 ^{Ba}	3.50 ± 1.14 ^{Ab}
FP-1	1	76.03 ± 2.35 ^{Aa}	-0.56 ± 0.06 ^{Aa}	8.08 ± 0.16 ^{Aa}	5.89 ± 2.35 ^{Ba}
	21	71.43 ± 0.66 ^{Aa}	-0.55 ± 0.05 ^{Aa}	7.43 ± 0.12 ^{Ba}	1.40 ± 0.66 ^{Aa}
FP-5	1	78.66 ± 0.80 ^{Bb}	-0.54 ± 0.10 ^{Aa}	8.48 ± 0.33 ^{Aa}	8.54 ± 0.81 ^{Bb}
	21	72.20 ± 0.36 ^{Aa}	-0.31 ± 0.06 ^{Aa}	8.26 ± 0.17 ^{Ba}	2.09 ± 0.34 ^{Aa}
MP-1	1	78.06 ± 1.49 ^{Bb}	-0.30 ± 0.13 ^{Aa}	7.53 ± 0.34 ^{Aa}	7.94 ± 1.48 ^{Bb}
	21	70.37 ± 0.19 ^{Aa}	-0.36 ± 0.13 ^{Aa}	7.48 ± 0.20 ^{Ba}	0.56 ± 0.21 ^{Aa}
MP-5	1	79.59 ± 0.40 ^{Bb}	-0.52 ± 0.13 ^{Aa}	7.77 ± 0.29 ^{Ab}	9.46 ± 0.41 ^{Bb}
	21	71.68 ± 1.43 ^{Aa}	-0.48 ± 0.06 ^{Aa}	6.66 ± 0.11 ^{Aa}	2.03 ± 1.30 ^{Aa}

C: Yogurt control sample; FP-1: Yogurt with 1% free persimmon extract; FP-5: Yogurt with 5% free persimmon extract; MP-1: Yogurt with 1% alginate-encapsulated persimmon; MP-5: Yogurt with 5% alginate-encapsulated persimmon.

$^{a–b}$ Different lowercase superscripts in the same row indicate significant differences among storage times ($p < 0.05$).

^{AB} Different uppercase superscripts in the same column indicate significant differences among yogurt samples at the same storage time ($p < 0.05$).

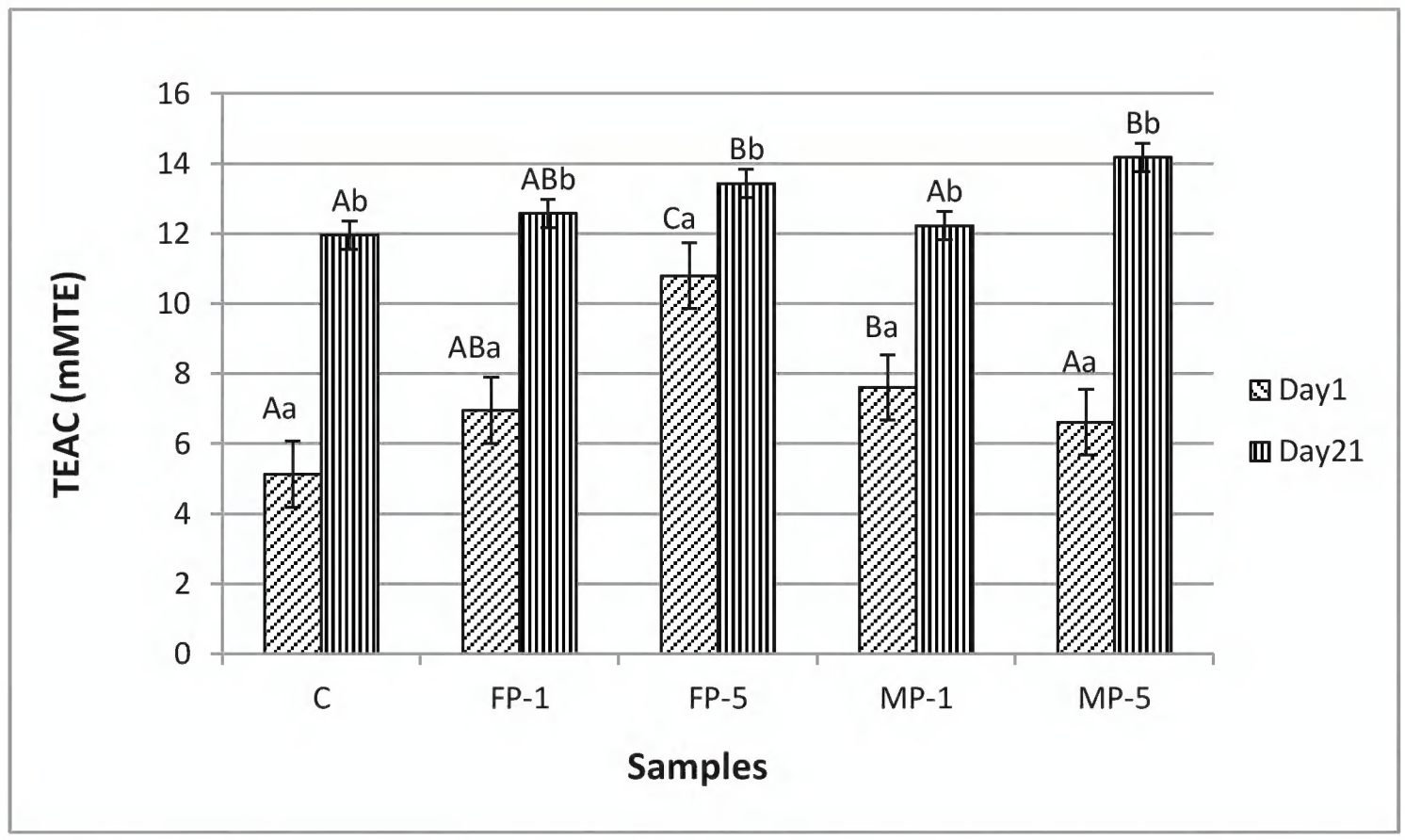

Figure 3. The total antioxidant activity of yogurt samples over the storage period. C: Yogurt control sample; FP-1: Yogurt with 1% free persimmon extract; FP-5: Yogurt with 5% free persimmon extract; MP-1: Yogurt with 1% alginate-encapsulated persimmon; MP-5: Yogurt with 5% alginate-encapsulated persimmon. [a–b] Different lowercase letters indicate significant differences between day 1 and day 21 within the same sample, while [A–C] different uppercase letters indicate significant differences among samples within the same storage day ($p < 0.05$), according to one-way ANOVA followed by Duncan's multiple range test.

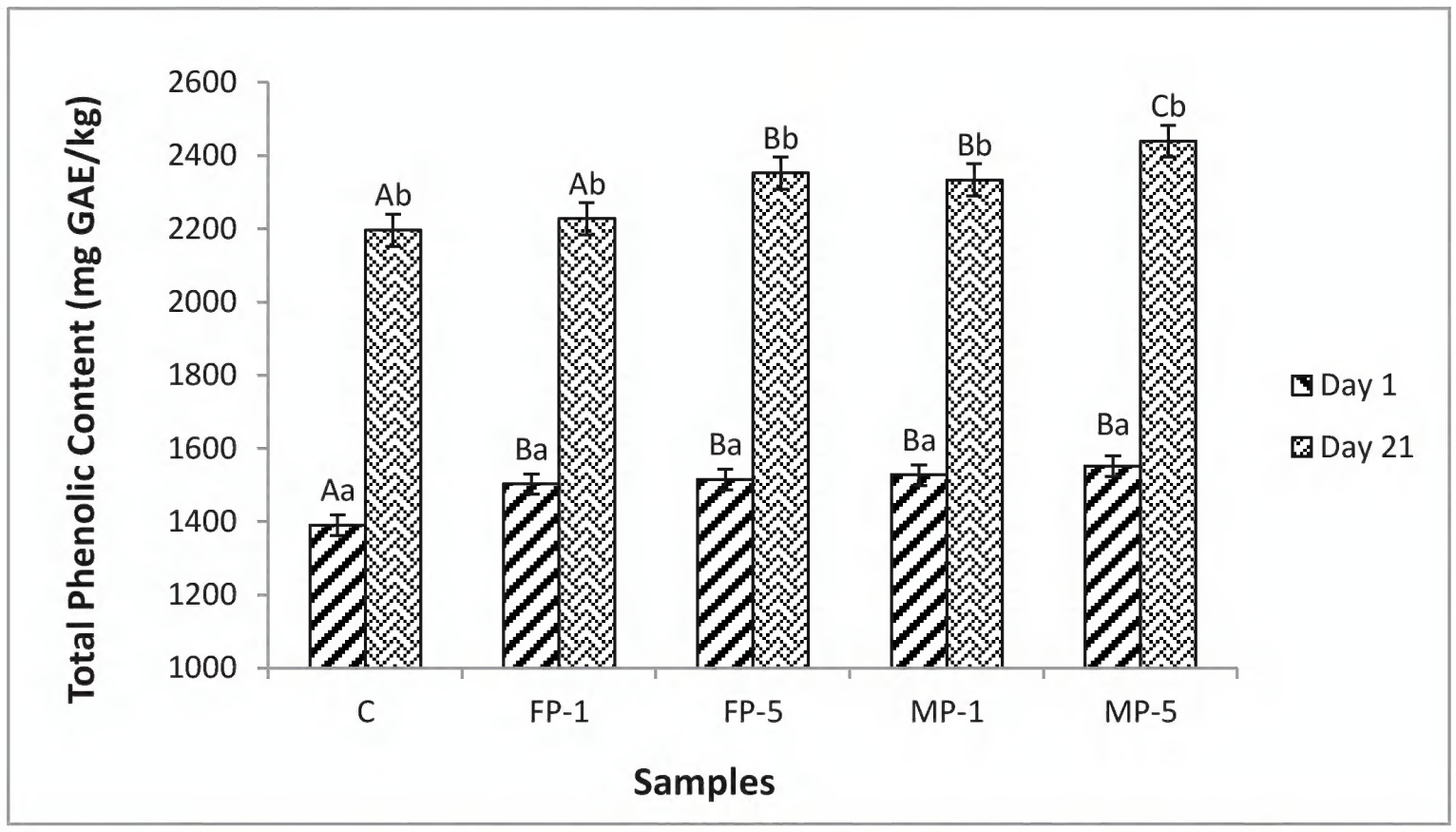

Figure 4. The total phenolic content of yogurt samples over the storage period. C: Yogurt control sample; FP-1: Yogurt with 1% free persimmon extract; FP-5: Yogurt with 5% free persimmon extract; MP-1: Yogurt with 1% alginate-encapsulated persimmon; MP-5: Yogurt with 5% alginate-encapsulated persimmon. [a–b] Different lowercase letters indicate significant differences between day 1 and day 21 within the same sample, while [A–C] different uppercase letters indicate significant differences among samples within the same storage day ($p < 0.05$), according to one-way ANOVA followed by Duncan's multiple range test.

variation between the samples and the time-dependent changes within the same sample were found to be significant ($p < 0.05$). The findings indicated that yogurt samples with encapsulated persimmon extracts generally had higher levels of phenolic compounds compared to the control sample, showing a statistically significant difference ($p < 0.05$). Similar results were reported by Yadav et al. (2018), Šeregelj et al. (2019), Okur (2023), Taşdemir and Gölge (2024). However, in the encapsulated form, the water absorption rate of the coatings could also be a contributing factor. According to other studies, an increase in the water absorption rate of coatings was associated with a higher rate of phenolic release (Delfanian and Sahari 2020).

Sensory evaluation

Fig. 5 illustrates the sensory attributes of the yogurt samples on the initial day of storage. The sensory evaluation revealed that during the storage period, all samples containing encapsulated persimmon extracts had a better sensory profile compared to the control samples ($p < 0.05$). This indicates that products enriched with biologically active compounds are highly accepted. Additionally, the addition of persimmon-alginate beads improved the color, appearance, and flavor of the yogurt products during the storage period. In the sensory evaluation, both the variation between the samples and the time-dependent changes were found to be significant ($p < 0.05$). The data shown in Fig. 6 regarding the overall acceptability scores of the yogurt samples during the storage period indicated that the highest score was achieved by treatment (MP-5), which involved yogurt with 5% alginate-encapsulated persimmon ($p < 0.05$). Therefore, the sensory evaluation results show that samples MP-5 and MP-1 not only contained the highest levels of biologically active compounds with antioxidant activity but also received the highest sensory ratings ($p < 0.05$). The results are consistent with the studies conducted by Yadav et al. (2018), El-Kholy et al. (2019), Ismail et al. (2023), Tumbarski et al. (2024), Abbasi Saadi et al. (2024) and Laina et al. (2025) which examined the encapsulation of different components in yogurt using the extrusion method.

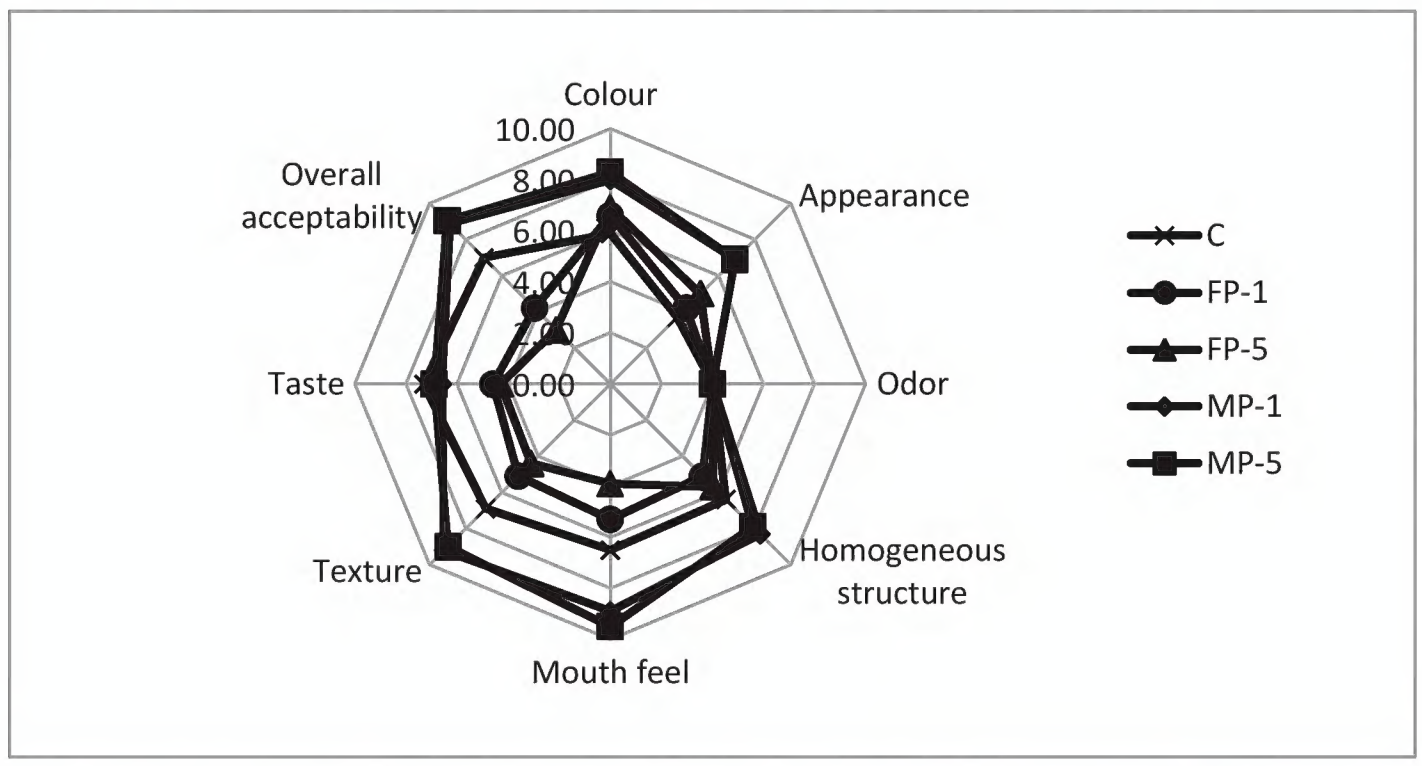

Figure 5. Sensory characteristics of the yogurt samples on the first day of storage. C: Yogurt control sample; FP-1: Yogurt with 1% free persimmon extract; FP-5: Yogurt with 5% free persimmon extract; MP-1: Yogurt with 1% alginate-encapsulated persimmon; MP-5: Yogurt with 5% alginate-encapsulated persimmon.

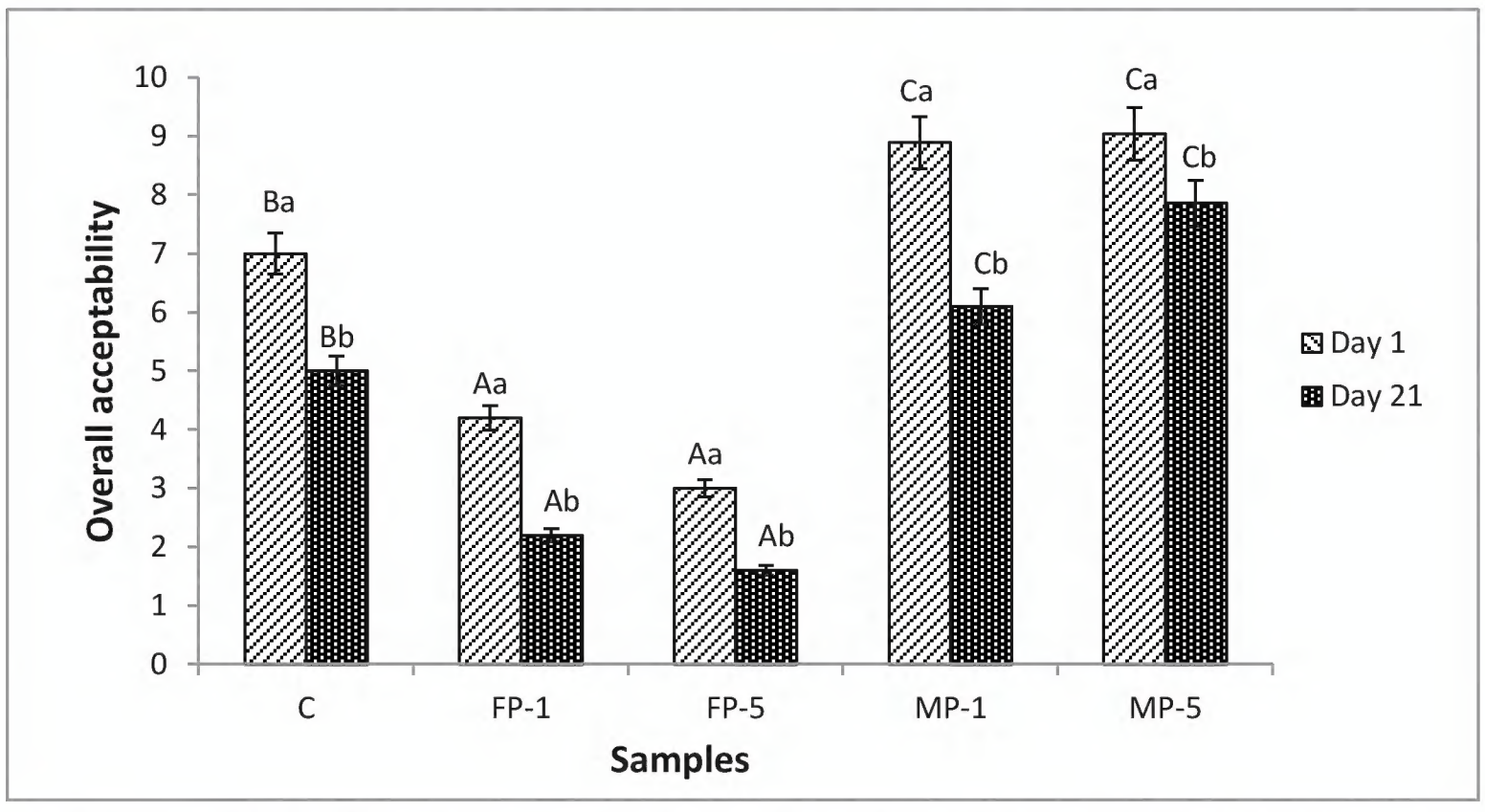

Figure 6. Overall acceptability of the yogurt samples throughout the storage period. C: Yogurt control sample; FP-1: Yogurt with 1% free persimmon extract; FP-5: Yogurt with 5% free persimmon extract; MP-1: Yogurt with 1% alginate-encapsulated persimmon; MP-5: Yogurt with 5% alginate-encapsulated persimmon. $^{a-b}$ Different lowercase letters indicate significant differences between day 1 and day 21 within the same sample, while $^{A-C}$ different uppercase letters indicate significant differences among samples within the same storage day ($p < 0.05$), according to one-way ANOVA followed by Duncan's multiple range test.

In order to better understand the holistic quality of the yogurt samples, the interactions between the analytical results were also evaluated. The results from different analytical methods exhibited meaningful interactions. The decrease in pH during storage was in parallel with an increase in titratable acidity, indicating active fermentation. This acidification was also associated with increased serum separation and reduced water holding capacity, likely due to protein destabilization. Furthermore, the antioxidant activity was strongly correlated with the total phenolic content, confirming the functional role of phenolics in the yogurt matrix. Changes in color, particularly in lightness and redness, may also be related to phenolic oxidation. These physicochemical changes were also reflected in the sensory evaluation; both MP1 and MP5 samples received higher scores, likely due to their lower syneresis and better texture stability compared to the other samples. Overall, the data show a strong interconnection between chemical composition, physical structure, and sensory quality of the yogurt samples.

Conclusion

This study specifies that encapsulation by the extrusion technique can significantly extend the stability of the persimmon fruit and has the potential to be used as a functional ingredient in yogurt. Furthermore, the stability of the tested fortified yogurts did not change until the end of the examination period. The greatest ΔE*ab values were observed on the first day of storage for the MP-5 and MP-1 samples, measuring 9.46 ± 0.41 and 7.94 ± 1.48, respectively ($p < 0.05$). Yogurts fortified with encapsulated persimmon extracts exhibited significantly higher antioxidant activity and phenolic content than those containing free extracts, likely due to better protection and increased bioavailability of phenolic compounds ($p < 0.05$). The application of persimmon beads in yogurt provides bioactive potential and offers consumers an optional functional food for their daily diet. The functional fermented yogurt enriched with alginate beads exhibited excellent organoleptic qualities and was introduced as a new product containing biologically active compounds that enhance positive health effects. Throughout the storage period, the highest overall acceptability scores were recorded for the MP-5 treatment, which contained 5% alginate-encapsulated persimmon, indicating its superior sensory appeal compared to other formulations ($p < 0.05$).

Author contributions

ODO and MA conducted the literature review, designed and carried out the experiments, analyzed the data, and wrote the manuscript.

Data availability

The data collected or analyzed during the study are all available in this published article.

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Conflict of interest

There are no competing interests present in this study.

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